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Effect of Cutting Parameters on Machinability of Titanium Grade 2 during Dry End Milling

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Abstract: The machining of commercially available titanium grade two in a dry environment using an uncoated solid carbide end mill is evaluated through this research. Using a one-variable-at-a-time (OVAT) method, the independent influences of cutting speed, feed rate, and depth of cut are assessed on the resultant cutting force, surface roughness, and the rate of tool degradation. The variables in this study were set to the ranges 65-105 m/min for cutting speed, 50-250 mm/min for feed rate, and 0.5-2.5 mm for depth of cut. As can be seen from these results, all parameters generally show increased cutting force, surface roughness and tool degradation with higher feed rates and depths of cut; however, the effects of cutting speed are moderate, with surface roughness exhibiting non-linear trends. By comparing the parameters' influence on the response, the depth of cut was found to be the most dominant factor affecting each machinability response. Next, the feed rate followed by the cutting speed was also shown to have some level of influence. Using the combined response behavior, effective machining ranges were identified to include: 75- 95 m/min cutting speed, 100-200 mm/min feed rate and 0.5-1.5 mm depth of cut. These machining ranges provide consistent levels of cutting forces, surface finishes and tool degradation, making them ideal for use in a variety of machining applications. The information provided within this study provides a good baseline for dry machining of titanium grade two and will be beneficial for use in future multi-parameter optimization studies.

Introduction

Titanium and its alloys have numerous commercial uses in high-performance engineering areas, including aerospace structures, biomedical implants, marine components and chemical processing equipment, due to their unique combination of strength-to-weight ratio, superior corrosion resistance, and good biocompatibility (Maier et al., 2020; Matuszak et al., 2023; Proud et al., 2023). In particular, among commercially pure titanium grades, Titanium Grade 2 has become the most widely accepted grade for pressure vessels, heat exchangers, and medical devices due to its favorable balance of mechanical strength, ductility, and corrosion resistance (Proud et al., 2023; Assis et al., 2024; Chintalapudi et al., 2024).

Although titanium and its alloys have many desirable properties, they are also very difficult to machine. The low thermal conductivity of titanium results in significant heat generation at the tool-chip interface. Also, due to titanium's high chemical reactivity, the cutting tool and the workpiece will adhere to each other. Finally, the low elastic modulus of titanium results in significant vibrations and deflections of the cutting tool during machining (Pradhan et al., 2022; Matuszak et al., 2023; Rauf et al., 2024). As a result of these characteristics, titanium requires high cutting forces, leading to high levels of tool wear, produces low surface finishes, and shortens the tool life, which all contribute to higher manufacturing costs and lower productivity (Yang et al., 2015; Khan & Maity, 2017; Ahmad et al., 2023).

The machining process typically used to produce complex shapes and high-precision parts from titanium alloys is end milling. End milling is a machining process that is highly sensitive to cutting parameters, including

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cutting speed, feed rate, and depth of cut. Therefore, improper selection of the above cutting parameters may significantly degrade surface integrity and accelerate tool deterioration (Wang et al., 2014; Liu et al., 2020; Ahmad et al., 2023; Matuszak et al., 2023; Al-Zubaidi et al., 2023; Rauf et al., 2024; Hu et al., 2025). Thus, a complete understanding of how individual and collective variations in machining parameters affect machinability characteristics is required to develop reliable and productive machining methodologies (Kilickap et al., 2017; Hu et al., 2025).

Many researchers have studied the machinability of titanium alloys, focusing on cutting forces, tool wear mechanisms, and surface quality. Past research indicated that both feed rate and depth of cut are the primary factors in determining cutting forces and tool wear rates, whereas cutting speeds are mainly responsible for temperature generation and surface finish (Yang et al., 2015; Kilickap et al., 2017; Ahmad et al., 2023; Rauf et al., 2024). While many researchers have utilized the optimization methodologies such as Taguchi methods, Response Surface Methodology (RSM), and artificial intelligence-based models for optimizing the machining parameters (Kilickap et al., 2017; Al-Zubaidi et al., 2023; Hu et al., 2025), a fundamental understanding of the independent effects of each cutting parameter is still needed to form the basis for those optimization methodologies (Khan & Maity, 2017; Khan & Maity, 2018).

A straightforward and systematic way to evaluate the individual impact of each machining parameter is to use the One Variable at a Time (OVAT) methodology, in which one parameter is varied while keeping all other parameters constant. Although OVAT cannot account for the interactions between variables, it is useful for identifying dominant parameters and establishing baseline machinability characteristics for difficult-to-machine materials such as titanium (Pradhan et al., 2022; Ahmad et al., 2023; Rauf et al., 2024).

This paper presents an experimental investigation of the machinability of Titanium Grade 2 during end milling with an uncoated solid carbide end mill under dry machining conditions. The independent effects of cutting speed, feed rate, and depth of cut on cutting forces, tool wear rate, and surface roughness are evaluated using the OVAT methodology. This paper provides valuable mechanistic insight into titanium milling behavior and serves as a foundation for future investigations into the development of optimized multi-variable machining methodologies (Kilickap et al., 2017; Chintalapudi et al., 2024; Hu et al., 2025).

Literature Review

There is no consistent understanding in the literature regarding how cutting parameters affect the machining of titanium alloys.

However, across many titanium machining studies, there seems to be some agreement on the relative importance of cutting parameters with respect to forces, surface roughness and tool wear. Specifically:

a) Feed rate and/or axial depth of cut have consistently been shown to dominate forces and surface roughness

b) Cutting speed has had a relatively complex role in machining titanium alloys. In some cases, it appears to have little effect on surface roughness or tool wear. However, in others, it has a much larger impact (Al-Zubaidi et al., 2023).

An example of this relationship can be seen in an end-milling study of Ti 6Al 4V under dry cutting conditions, where surface roughness was shown to be primarily dependent on feed rate, followed by axial depth of cut, and finally speed (Al-Zubaidi et al., 2023). Similarly, in a micro-milling study of titanium grades 9 and CP Ti, feed rate was again identified as the primary factor contributing to surface roughness, followed by cutting speed and depth of cut (Khan et al., 2023; Assis et al., 2024).

These findings are consistent with results that depth of cut and feed rate are the two cutting parameters that most strongly affect cutting forces, surface roughness and tool wear. Data also indicate that speed has a moderate but important influence on these parameters.

Table 1. Typical parameter influence on Ti milling responses.

Response	Most influential parameters (typical)	Citations
Cutting force	Depth of cut, feed and speed secondary	(Al-Zubaidi et al., 2023; Khan et al., 2023; Donenbayev et al., 2025)
Surface roughness Ra	Feed rate primary, depth and speed secondary/non-linear	(Al-Zubaidi et al., 2023; Khan et al., 2023; Ahmad et al., 2023; Panin et al., 2025; Donenbayev et al., 2025)
Tool wear/ tool life	Cutting speed is very influential, higher feed/depth accelerates	(Matuszak et al., 2023; Pradhan et al., 2023; Younas et al., 2024; Hu et al., 2025)

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Non-Linear Speed Effects

High-speed milling of Ti-6Al-4V exhibited non-monotonic behavior with respect to speed: Ra decreased with increasing speed until it reached a plateau, after which it increased again due to tool wear and thermal damage (He et al., 2024; Matuszak et al., 2023; Wang et al., 2025). The non-linear behavior observed between speed and roughness, as well as the transformation of the surface layer during high-speed cutting of Ti-6Al-4V, were also noted in previous studies (Wang et al., 2025). These results support the previously observed non-linear response of surface roughness to speed in the OVAT study.

Dry, Cryogenic and CO_2 Assisted Milling of CP Ti

The use of Supercritical CO_2 alone resulted in greater than emulsion tool wear when milling Grade 2 CP Titanium using shoulder milling (Proud et al., 2023). However, the application of both CO_2 and MQL increased tool life by up to 245% (Proud et al., 2023). Additionally, the effective range of cutting speeds was established as at or below approximately 115 m/min (Proud et al., 2023), further highlighting the need to use moderate cutting speeds with this alloy. Dry cutting of commercially pure titanium using micro cutting techniques has also shown that, under specific conditions, dry cutting can outperform wet cutting due to its ability to use higher feeds (Assis et al., 2024). Utilizing MQL and cryogenic techniques for machining titanium alloys generally demonstrates lower friction, lower cutting temperatures and less tool wear than dry machining (Fersi et al., 2024; Pradhan et al., 2023; Younas et al., 2024).

Experimental Design and Optimization

Titanium machining studies have transitioned from OVAT-based design to experimental designs such as Taguchi designs and full factorial designs, as well as multi-objective optimization methods (such as RSM, Grey Relational Analysis, Neural Models) to better understand the interactions among parameters and to achieve optimal machinability across multiple responses (Khan et al., 2023; Al-Zubaidi et al., 2023; Ahmad et al., 2023; Panin et al., 2025; Donenbayev et al., 2025). Optimal machining conditions for ultrasonic-assisted milling and high-speed milling of Ti-6Al-4V are generally characterized by moderate to low cutting speeds, moderate feed rates, and moderate to shallow cutting depths (Matuszak et al., 2023; Panin et al., 2025; Wang et al., 2025). Therefore, the defined "effective window" for CP Grade 2 dry milling (using moderate speeds, moderate feeds, and shallow to medium cutting depths) aligns with the optimization ranges used for other titanium alloys.

Overall, existing research regarding the machining of titanium and commercially pure titanium under dry or near-dry conditions supports the primary trends presented within study: that the feed rate and cutting depth will have a dominant effect on the forces generated, surface roughness, and tool wear during machining; whereas, the cutting speed will exhibit a moderate influence and often a non-linear effect, particularly on surface finish and wear. Furthermore, the provided parameter window for dry-end-milling of Ti Grade 2 with uncoated carbide is consistent with broader optimization findings for titanium alloys and provides a viable reference point for future multi-parameter and coolant-assisted optimization efforts.

Materials and Methodology

Workpiece Material

The workpiece material used in the present investigation was commercially pure Titanium Grade 2, supplied as a rectangular plate with dimensions 100 mm × 100 mm × 10 mm. Titanium Grade 2 is widely used in aerospace, chemical, and biomedical applications due to its excellent corrosion resistance, moderate strength, and good formability (Khan & Maity, 2018; Proud et al., 2023; Assis et al., 2024). However, its low thermal conductivity and high chemical affinity with cutting tools make it challenging to machine (Maier et al., 2020; Pradhan et al., 2022; Chintalapudi et al., 2024). These properties make Titanium Grade 2 an evaluation of machinability behaviour under end milling conditions (Matuszak et al., 2023; Ahmad et al., 2023).

Commercially Pure Titanium Grade 2 was used as the workpiece material in this research study. It was provided in a rectangular block form (100 mm x 100 mm x 10 mm) and has been extensively utilized in aerospace, chemical, and biomedical industries because of the superior corrosion resistance of the alloy, moderate strength, and formability (Assis et al., 2024; Proud et al., 2023; Khan & Maity, 2018). Due to low thermal conductivity and high chemical affinity with cutting tools, however, titanium alloys are difficult to machine (Pradhan et al., 2022; Chintalapudi et al., 2024; Maier et al., 2020), which makes them suitable for evaluation of machinability behavior under end milling conditions (Ahmad et al., 2023; Matuszak et al., 2023).

Machine Tool and Experimental Setup

All experimental tests were conducted on an MTAB Maxmill Plus CNC Vertical Machining Centre. A solid carbide end mill was attached to the spindle via a standard collet chuck to ensure precise, stable tool positioning. The Titanium Grade 2 workpiece was firmly

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secured to the CNC machine table to prevent movement during milling.

All milling processes were performed under dry-cutting conditions to mimic the environment in aerospace and biomedical manufacturing applications, where the use of cutting fluids is limited or prohibited. The same tool geometry, clamping fixtures, and machining conditions were used throughout the tests to minimize variability in the data and maximize repeatability of the results.

Figure 1. Experimentation Set-up on MTAB Maxmill Plus VMC.

Machining Parameters and Their Levels

Three machining parameters affecting the machinability of Titanium Grade 2 were studied using the OVAT method. These parameters, along with their various levels, were selected from recommended guidelines by the tool manufacturer, from preliminary experimental studies and from general practices in the literature as described by Wang et al., 2014; Kilickap et al., 2017 and Matuszak et al., 2023.

These three machining parameters (cutting speed, feed rate, and depth of cut) had the following five different levels:

a) Cutting Speed (Vc): 65, 75, 85, 95, and 105 m/min
b) Feed Rate (f): 50, 100, 150, 200, and 250 mm/min
c) Depth of Cut (ap): 0.5, 1.0, 1.5, 2.0, and 2.5 mm

As part of the OVAT methodology, only one machining parameter was changed at a time, while all other parameters remained at their baseline values during the experimentation phase. Thus, the effect of each machining parameter on the machined response could be evaluated independently, as described by Ahmad et al. (2023), Khan & Maity (2017), and Rauf et al. (2024). All experimental conditions were controlled so that the machining conditions, tool geometry, workpiece material, machine tool, and dry cutting condition would remain consistent throughout all tests to obtain repeatable results, as described by Maier et al. (2020) and Matuszak et al. (2023).

Measurement of Machining Responses

a) Cutting forces were measured using a Kistler 5070A piezoelectric dynamometer, capable of capturing Fx, Fy and Fz components with high accuracy. The resultant cutting force was computed as:

$$FR = \sqrt{(Fx)2} + \sqrt{(Fy)2} + \sqrt{(Fz)2}$$

b) The tool wear rate was determined by calculating the difference in cutter mass before and after each cut, then converting this mass loss to volumetric wear by utilizing the known carbide density (15.66 mg/mm³).
c) Averaged values for Ra were obtained from 3 individual measurements for each machined slot using a stylus-type surface roughness measuring instrument (Mitutoyo SJ-410 that accounted for Titanium's elastic recovery.

Results and Discussion

The Machining Performance of Commercially Pure Titanium Grade 2 During End Milling Using Uncoated Solid Carbide End Mills Was Evaluated Using a One Variable at a Time Experimental Approach to Determine the Individual Effects of Cutting Speed, Feed Rate and Depth of Cut (Khan & Maity, 2017; Ahmad et al., 2023; Rauf et al., 2024). Responses studied were cutting forces, tool wear rates and surface finish (surface roughness), all of which have been identified as important machining performance characteristics for titanium alloys (Wang et al., 2014; Kilickap et al., 2017; Matuszak et al., 2023). The discussion of the experimental data is presented in subsequent sections to determine the most influential variables and describe the experimental machining behaviour (Yang et al., 2015; Hu et al., 2025).

Effect of Cutting Speed

OVAT for Cutting speed Vs Resultant Cutting Force

Table 2 presents the variation of resultant cutting force with respect to cutting speed, while keeping the feed rate (150 mm/min) and depth of cut (1.5 mm) constant. It is observed that the resultant cutting force

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Table 2. OVAT for Cutting speed.

Sr. No	Cutting Speed (mm/min)	Feed Rate (mm/min)	Depth of Cut (mm)	Resultant Cutting Force (N)
1	65	150	1.5	241.67
2	75	150	1.5	257.66
3	85	150	1.5	277.35
4	95	150	1.5	311.67
5	105	150	1.5	319.41

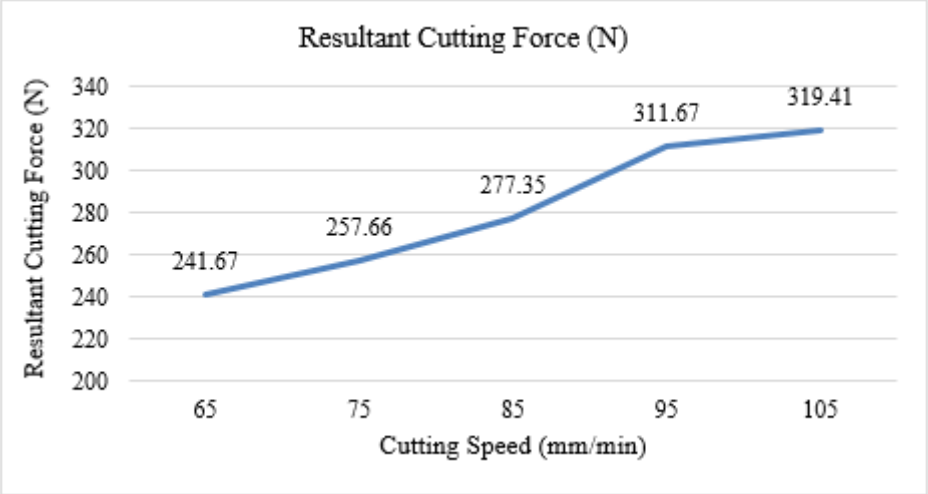

Figure 2. Cutting speed Vs Resultant Cutting Force.

Table 3. OVAT Surface Roughness.

Sr. No	Cutting Speed (mm/min)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface Roughness (Ra)
1	65	150	1.5	1.30
2	75	150	1.5	1.25
3	85	150	1.5	1.38
4	95	150	1.5	1.55
5	105	150	1.5	1.58

increases consistently with increasing cutting speed from 65 to 105 m/min.

When the cutting speed was set to 65 m/min, the resulting cutting force recorded was 241.67 N. At an increased cutting speed of 75 m/min, the cutting force rose by 16 N to 257.66 N. The moderate increase can be explained by both the higher strain rate and the increased friction between the tool and the chip. Similar increases were observed when the cutting speed was raised to 85 m/min, at which the cutting force reached 277.35 N. The cutting force continued to stabilize.

As the cutting speed was further increased to 95 m/min, the cutting force increased substantially, reaching 311.67 N. This large increase in cutting force can be primarily explained by increased thermal concentrations at the tool-chip interface and increased chip flow resistance. When the cutting speed was increased from 95 m/min to 105 m/min, the cutting force increased slightly (from 319.41 N to 320.41 N). The small increase in cutting force is indicative of partial thermal softening of the workpiece material, which tends to counteract further increases.

Generally, the rate of growth of the cutting forces remains relatively steady from 75 to 95 m/min. At very slow cutting speeds, cutting conditions are dominated by adhesion, whereas at very fast cutting speeds, they become increasingly thermally stressed. Thus, as indicated by the cutting force behavior, the cutting speed range of 75-95 m/min is considered a useful and stable operating region for machining Titanium Grade 2 under the selected conditions.

OVAT for Cutting speed Vs Surface Roughness

The variation in surface roughness (Ra) with respect to cutting speed, while keeping the feed rate (150 mm/min) and depth of cut (1.5 mm) constant, is shown in Table 3. The surface roughness trends nonlinearly with increasing cutting speed.

When the cutting speed was increased from 65 mm/min to 75 mm/min, the surface roughness of the manufactured parts (Ra) decreased slightly, from 1.30 µm

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to 1.25 µm. Thus, it appears that increasing the cutting speed from 65 mm/min to 75 mm/min improved the finish of the manufactured parts. The decrease in surface roughness at this higher cutting speed may have been caused by improved chip formation and/or greater localized thermal softening of the workpiece. These two factors would reduce friction between the tool and the workpiece during machining operations, resulting in smoother cutting.

An increase in cutting speed beyond 75 mm/min resulted in increases in surface roughness, with a 10 mm/min increase to 85 mm/min causing an increase in surface roughness from 1.25 µm to 1.38 µm; a 10 mm/min increase to 95 mm/min resulting in an increase in surface roughness from 1.38 µm to 1.55 µm; and a 10 mm/min increase to 105 mm/min resulting in an increase in surface roughness from 1.55 µm to 1.58 µm. This increase in surface roughness at higher cutting speeds can be attributed to the additional heat generated at the tool-chip interface. Excessive heat generation increases the rate of tool wear and leads to cutting-edge degradation. A degraded cutting edge will produce uneven markings on the surface of the part being manufactured as it wears down, increasing the surface roughness of the finished part.

In total, it has become clear that in the area between a cutting speed of 65-75 mm/min, the rate of change of surface roughness is relatively low and constant, whereas with speeds greater than 75mm/min, the surface roughness will increase rapidly. Therefore, when the primary consideration for machining is to produce the lowest possible surface roughness, then 75-95 mm/min would appear to be the most optimum cutting speed range in the machining conditions used.

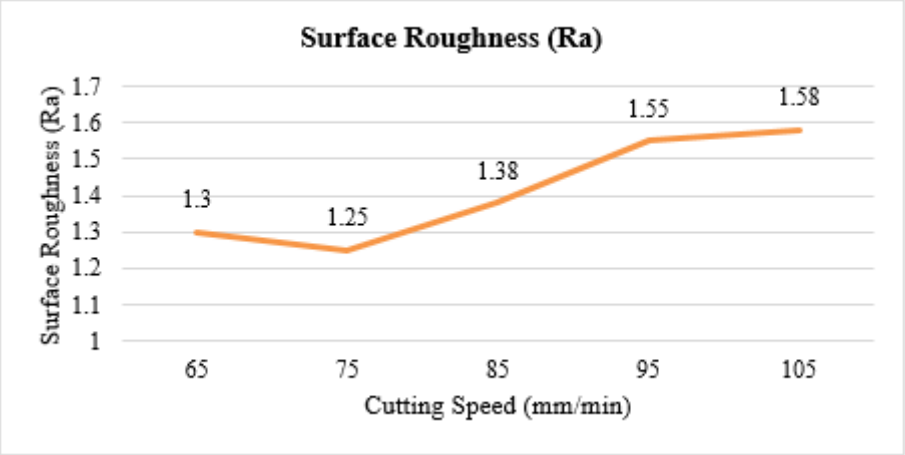

Figure 3. Cutting speed Vs Surface Roughness.

Table 4. OVAT Tool Wear Rate.

Sr. No	Cutting Speed (mm/min)	Feed Rate (mm/min)	Depth of Cut (mm)	Tool Wear Rate (mm³/min)
1	65	150	1.5	0.52
2	75	150	1.5	0.59
3	85	150	1.5	0.72
4	95	150	1.5	0.88
5	105	150	1.5	0.98

OVAT for Cutting Speed vs. Tool Wear Rate

The table shown below illustrates how the tool wear rate (TWR) varies with cutting speed when the feed rate (150 mm/min) & depth of cut (1.5 mm) are kept constant. It can be seen from the table that as the cutting speed increases, the tool wear rate increases.

When using a cutting speed of 65 mm/min, the tool wear rate was 0.52 mm³/min. At an increased cutting speed of 75 mm/min, the tool wear rate increased to 0.59 mm³/min, indicating that thermal factors have begun to affect tool wear.

The same can be said for the increased cutting speed to 85 mm/min where the tool wear rate was 0.72 mm³/min; this increase shows the increasing abrasive and adhesive characteristics of the tool-chip interface.

A significant increase in tool wear rate was observed with a cutting speed of 95 mm/min (tool wear rate = 0.88 mm³/min) and a cutting speed of 105 mm/min (tool wear rate = 0.98 mm³/min). The large increase in the tool wear rate is due to excessive heat generation and longer tool-chip contact times, which promote both flank wear and diffusion wear, as well as micro-chipping of the tool's cutting edge.

Overall, the rate of increase of the tool wear rate is

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relatively moderate between 75 and 95 mm/min, whereas a slope increase is observed beyond 85 mm/min, indicating unstable tool performance at higher cutting speeds. Hence, based on tool wear considerations, the cutting speed range of 75–95 mm/min can be considered as the effective operating region under the selected machining conditions.

Effect of Feed Rate

The effects of varying feed rate while maintaining constant cutting speed (85 m/min), and depth of cut (1.5 mm) on resultant cutting forces, surface roughness, and tool wear rate are provided in Table 5.

It can be seen that feed rate has an important influence on all three machinability factors (resultant cutting force, surface roughness and tool wear rate).

With the feed rate increasing from 50 to 250 mm/min, there was a steady increase in resultant cutting force from 241.67 N to 320.24 N. An increase in resultant cutting force is primarily due to an increase in uncut chip thickness, which increases the required shear force and results in increased mechanical load on the cutting edge. The resultant cutting force increases at a moderate rate up to a feed rate of 150 mm/min. Beyond 150 mm/min the rate of increase is significantly more rapid.

When the feed rate was increased from 50 to 100 mm/min, surface roughness decreased slightly from 1.30 µm to 1.26 µm, indicating better surface finishes due to improved stability under cutting conditions. However, with continued increases in feed rate, surface roughness rose to 1.64 µm at 250 mm/min. Surface quality deteriorated as a result of an increase in scallop height, vibration and feed mark formation at higher feed rates.

An increase in feed rate resulted in an increase in tool wear rate, from 0.52 mm^3/min to 0.82 mm^3/min. Increased feed rates also increase mechanical stresses and friction between the tool and chip, thereby enhancing both abrasive and adhesive wear mechanisms. The increase in tool wear rate is more pronounced at feed rates above 150 mm/min, suggesting that tool life decreases as feed rate increases.

Effect of Depth of Cut

Table 6 shows how the cutting force, surface roughness, and tool wear rate are influenced by varying the cutting depth (with the cutting speed and feed rate remaining constant). The results indicate that the cutting depth significantly influences each of the three machining performance measures discussed.

An increase in cutting depth from 0.5 mm to 2.5 mm resulted in an upward trend in the measured cutting force from 241.67 N to 314.82 N. An increase in the size of the tool-workpiece contact area and the resulting increase in the cross-sectional area of the chip result in increased shear stress required to remove the material being machined, thus leading to the increased cutting force observed. The magnitude of increase in cutting force was moderate until a cutting depth of 1.5 mm and then became less pronounced, indicating some degree of stabilizing the cutting force loading as the depth of cut continues to increase.

Surface roughness also demonstrated an increase in response to an increase in the cutting depth. The Ra values were found to increase from 1.30 µm at a cutting depth of 0.5 mm to 1.74 µm at a cutting depth of 2.5 mm. Increased cutting forces and vibrations occur at larger cutting depths, which can lead to increased tool deflection and irregular tool marks on the surface of the work piece during machining, ultimately decreasing the surface quality.

Similarly, the tool wear rates demonstrated an increase with an increase in the cutting depth, increasing from 0.52 mm^3/min to 1.09 mm^3/min. The tool wear rates are generally expected to increase when there are increases in both mechanical and thermal stresses associated with the cutting edge of the tool, particularly at the higher cutting depths where increased tool wear rates may be anticipated as a result of increased flank wear and adhesive type wear processes occurring on the cutting edge. A relatively sharp increase in tool wear rate is apparent beyond a cutting depth of 1.5 mm, indicating that tool life will decrease as the cutting depth continues to increase.

Comparative Influence of Machining Parameters

An examination of the effects of cutting speed, feed rate and depth of cut through an OVAT analysis of Titanium Grade 2 when using dry end milling revealed the relative effects of these parameters on the material's machinability. The data in sections 4.1-4.3 demonstrated that all three machining parameters have a significant effect on the resultant cutting force, surface finish (surface roughness) and tool wear rate. However, the magnitude and sensitivity of the influence of the machining parameters varied. The machining parameter with the greatest influence on the measured responses was depth of cut, followed by feed rate and then cutting speed, although cutting speed had a relatively less influential but still measurable effect on both surface finish and tool wear.

The relative dominance of machining parameters on the measured responses can be summarized as follows:

1. Resultant Cutting Force: Depth of cut > Feed rate > Cutting speed

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2. Surface Roughness (Ra): Feed rate ≈ Cutting speed > Depth of cut

3. Tool Wear Rate (TWR): Depth of cut ≥ Cutting speed > Feed rate

The machining parameters exhibit a direct relationship with the measured responses. The influence of the machining parameters is as follows:

Depth of cut controls the tool-workpiece contact area and the cross-sectional area of the chip generated during machining. As such, increasing the depth of cut will result in higher mechanical loads, vibrations, and tool wear.

The feed rate controls the thickness of the uncut chip. A greater feed rate results in a thicker uncut chip, which will result in increased cutting force and decreased surface quality.

Cutting speed controls the thermal conditions at the tool-chip interface. Therefore, an increase in cutting speed will result in a decrease in cutting force and will have a more pronounced effect on tool wear and surface roughness than cutting force.

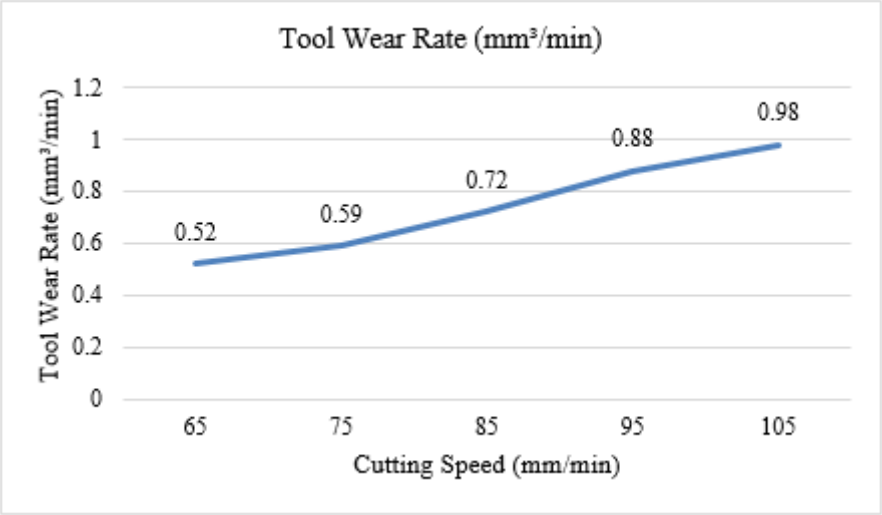

Figure 4. Cutting speed vs. tool wear rate.

Table 5. OVAT for Feed Rate vs Machinability Response.

Sr. No.	Feed Rate (mm/min)	Resultant Cutting Force (N)	Surface Roughness, Ra (µm)	Tool Wear Rate (mm³/min)
1	50	241.67	1.30	0.52
2	100	252.66	1.26	0.57
3	150	269.41	1.39	0.72
4	200	305.16	1.53	0.79
5	250	320.24	1.64	0.82

These trends agree with previous research on the machining of titanium alloys under dry machining conditions. In this work, it was determined that the depth of cut is the most influential machining parameter with respect to the cutting force and that feed rate and cutting speed together determine the surface quality and the extent of tool degradation.

Conclusions

Commercially pure titanium Grade 2 has been studied for machinability in dry end milling using uncoated solid carbide end mills. The effect of each of the three independent parameters, cutting speed, feed rate and depth of cut, on three dependent parameters, cutting force, surface roughness and tool wear rate, has been

Table 6. OVAT for Depth of Cut vs Machinability Responses.

Sr. No.	Depth of Cut (mm)	Resultant Cutting Force (N)	Surface Roughness, Ra (µm)	Tool Wear Rate (mm³/min)
1	0.5	241.67	1.30	0.52
2	1.0	260.24	1.35	0.71
3	1.5	282.16	1.59	0.92
4	2.0	313.35	1.68	1.05
5	2.5	314.82	1.74	1.09

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evaluated. The major findings of this work are as follows:

1. There is a moderate relationship between cutting speed and machining performance. There is a linear trend in cutting speed with respect to cutting force and tool wear, whereas there is a non-linear trend in surface roughness, which initially improves up to a point and then declines at higher cutting speeds. Therefore, a cutting speed of 75–95 m/min is found to be the optimal range that provides the best compromise between surface finish and tool life.
2. The effect of feed rate on the response is significant. In addition to a direct increase in cutting force and tool wear, increasing the feed rate also degrades surface finish due to increased chip loads and vibrations. As such, a recommended feed rate range of 100–200 mm/min can produce stable cuts with good surface quality.
3. The effect of the depth of cut is the largest. When the depth of cut is increased, both cutting force and
4. Surface roughness increases significantly, primarily due to greater tool-workpiece interaction and the mechanical stresses associated with larger depths of cut. Therefore, a recommended range of 0.5-1.5 mm is established for stable machining of commercially pure titanium.
5. Overall parameter influence follows the order: Depth of cut > Feed rate > Cutting speed for cutting force and tool wear, while feed rate and cutting speed dominate surface roughness.

The OVAT study provides clear baseline insight into the dry end milling behaviour of Titanium Grade 2. The identified parameter ranges offer practical guidance for stable machining and form a foundation for future multi-parameter optimisation and advanced lubrication studies.

Conflict of interest

None

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